A Propose-and-revise System for Real-time Traffic Management

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ABSTRACT: The aim of this paper is to describe an intelligent system for the problem of real time road traffic control. The purpose of the system is to help traffic engineers in the selection of the state of traffic control devices on real time, using data recorded by traffic detectors on motorways. The system follows an advanced knowledge-based approach that implements an abstract generic problem solving method, called propose-and-revise, which was proposed in Artificial Intelligence, within the knowledge engineering field, as a standard cognitive structure oriented to solve configuration design problems. The paper presents the knowledge model of such a system together with the strategy of inference and describes how it was applied for the case of the M-40 urban ring for the city of Madrid.

KEYWORDS: Real-time traffic control, Knowledge-based decision support systems, Reusable problem-solving methods.

1.INTRODUCTION: TRAFFIC MANAGEMENT

Control centers for traffic management are usually connected on-line to devices such as detectors on roads, cameras, traffic lights, etc. in such a way that operators can supervise the state of the road by consulting data bases with recent information from detectors and can modify the state of control devices. The effective use of these traffic monitoring and management facilities requires sophisticated support tools for on-line operators, to help them in dealing with the information complexity and the diversity of sensors and control devices. In particular, expert systems for decision support have recently been successfully introduced in this field, [Cuena et al., 92], [Deeter and Ritchie, 1993], [Molina et al., 1995].

Figure 1 shows a typical infrastructure for real-time traffic control that can be found in different cities. There are detectors on major roads recording several traffic measures such as speed (km/h), flow (vehicle/h) and occupancy (percentage of time the sensor is occupied by a vehicle). The distance between successive sensors on a freeway is usually about 500 meters. The information arrives periodically to the control center (e.g., every minute). The control center receives also information about the current state of control devices.

Control devices include traffic signals at intersections, traffic signals at on-ramps, variable message signs (VMS) that can present different messages to drivers (e.g., warning about an existing congestion or alternative path recommendation), radio advisory systems to broadcast messages to drivers, and reversible lanes (i.e., freeway lanes whose direction can be selected according to the current and expected traffic demand). In the control center, operators interpret sensor data and detect the presence of problems and their possible causes. Problems are congested areas at certain locations caused by lack of capacity due to accidents, excess of demand (like rush hours), etc. In addition, operators determine control actions to solve or reduce the severity of existing problems. For instance, they can increase the duration of a phase (e.g., green time) at a traffic signal, or they may decide to show certain messages on some VMSs to divert traffic.

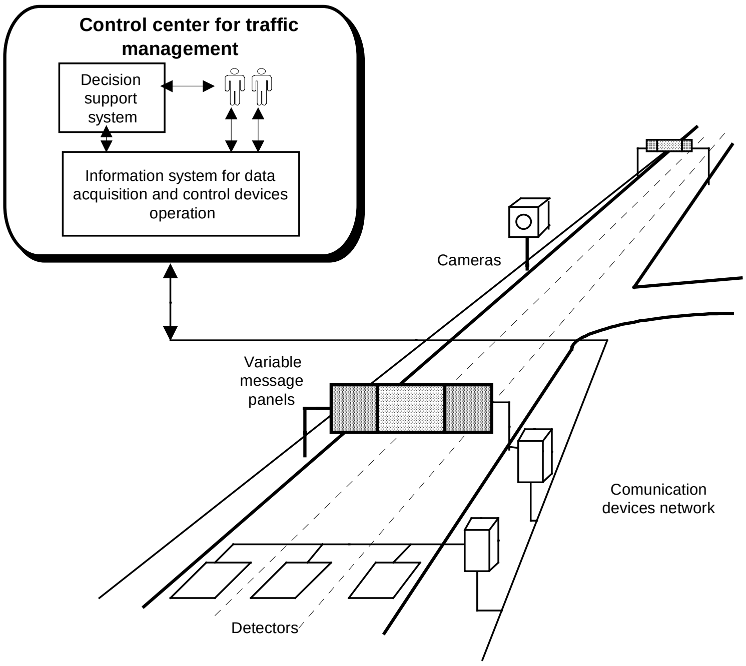

Figure 1: Typical information infrastructure for real-time traffic management.

This problem can be characterized as a configuration design problem where, from an initial situation (the traffic state at different locations) a complete design must be defined as a set of states for control devices (e.g., messages for each VMS panel or states of traffic signals at on-ramps), considering consistency conditions about messages and traffic. In addition to that, the qualitative nature of messages together with specific criteria (area-dependent) based on a heuristic knowledge of the area for certain panels makes difficult the use of generic algorithmic solutions for this problem. Thus, an approach from the field of Artificial Intelligence, in particular from the domain of knowledge based systems, can be applied to solve this problem.

2. METHODS IN ARTIFICIAL INTELLIGENCE FOR CONFIGURATION PROBLEMS

In the past 15 years, the Artificial Intelligence field has provided a set of specialized advanced problem solving methods that can be useful for a set of established classes of problems. These results have been produced within the knowledge engineering community where researchers were interested in knowledge sharing and reuse in order to decrease the effort in building new knowledge based applications. One of the main conclusions of this research was that, in order to build a new knowledge-based system, is useful to use a modelling approach to emulate how a human expert solves problems in a particular professional area. For this purpose, it is necessary to describe such a model in a cognitive level (called knowledge level by A. Newell [Newell 82]) by using certain particular description entities closer to human thinking than computer processing. This idea was followed by different software tools and methodologies (e.g., KADS [Schreiber et al., 93]).

These results carried out an interesting proposal about how to reuse problem-solving knowledge. Authors proposed the concept of Problem Solving Method (PSM), an abstract cognitive structure specialized in classes of problems, derived of original proposals of different authors such a J. McDermott [McDermott, 88], B. Chandrasekaran [Chandrasekaran et al., 92] and J. Clancey [Clancey, 92]. Each PSM defines a knowledge intensive architecture together with the reasoning process to solve a class of problems. Since then, several PSMs were identified as standard typical intuitive reasoning processes followed by human experts in certain kind of problems. For this purpose, problems were divided in classes considered as tasks associated to different PSMs [Breuker, Van de Velde, 94]. For example, a diagnostic task can be solved by the cover-and-diferenciate PSM or a classification task can be solved by the establish-and-refine PSM.

In particular, within constructive problems, a configuration design task can be solved by the propose-and-revise PSM [Marcus, McDermott, 89]. This method belongs to a family similar methods for configuration problems (propose-critique-and-modify, propose-and-exchange, etc.) and simulates how a person proposes in a first step a design and, then in a second step, she analyzes whether this proposal violates some constraints. If so, a remedy is applied based on heuristic knowledge in order to modify the original proposal. This process is repeated until, if possible, a satisfactory configuration is found. Thus, the method emulates how a person develops a tentative search supported by specialized knowledge. In particular, the abstract structure of this method assumes the existence of three kinds of knowledge to be represented with three knowledge bases:

- *Derivation knowledge*. This is knowledge to propose a design that includes specific criteria to deduce a complete design from initial specifications. This knowledge can be formulated as direct relations between initial data, intermediate parameters and final parameters (numerical or qualitative) that describe how each parameter obtains its value from the values of other parameters. One important requirement of this knowledge is that this relations do not have to include loops to avoid circular calculation.

- *Compatibility knowledge*. This knowledge is used to verify a proposed design and includes a set of criteria to identify incompatible cases. This knowledge can be formulated as a set of constraints where each constraint expresses the set of incompatible conditions.

- *Remedy knowledge*. This knowledge includes a set of criteria to solve a violation detected in the design. This knowledge can be represented as rules that define types of remedy actions (fixes) to solve each type of violation. Together with this knowledge, there are a set of preference criteria based on priorities to select fixes when different fixes can be used for the same violation.

This approach presents some similarities with the idea of Truth Maintenance Systems TMS. In general, a TMS ([Mc Allester 1980], [Doyle 1979], [De Kleer 1986]) keeps a predefined set of declarations in terms of consistency, i.e. if in a given state the set of assumed TMS nodes is inconsistent the TMS identifies the assumed nodes responsible for the inconsistency and modifies the assumptions to keep the compatibility. In fact, the TMS approach was originally considered as a possible solution for the problem of VMS panels [Cuena 97]. However, the propose-and-revise method is a solution that is defined at a lower level of abstraction closer to the design problem, which make easier its application, and it proposes an explicit representation for heuristic knowledge to remedy violations, which can make easier its application for the traffic control problem.

3. A METHOD FOR REAL-TIME TRAFFIC CONTROL

The propose-and-revise method was applied to build an information system that help operators in the selection of messages for motorway panels on real time in the M-40 urban ring in Madrid. This section describes how this method was applied in this domain.

3. 1. THE KNOWLEDGE MODEL

The system includes a conceptual vocabulary to establish the basic traffic terminology used by the knowledge bases. This vocabulary includes, among others, the following main concepts:

- *Panel:* This concept helps to identify the set of panels on the road and contains information such as the potential valid messages for the panel and current message on the panel.

- *Message*: The message concept defines a particular message to be written on a particular panel and contains information such as type (incident, traffic jam, etc.), text, priority level, etc.

- *Road section*: This concept identifies a section of the road corresponding to a point where a detector is located, and contains the different measures recorded by the detector (speed, flow, occupancy) besides other information related to the geometry of the road.

- *Path*: This concept defines a path as sequence of road sections and includes information such as the state of the path (free, with an accident, congestion, etc.), the travel time, sections, etc.

According to the propose-and-revise strategy, the method includes the following three knowledge bases: derivation, compatibility and remedy.

Derivation Knowledge Base

This knowledge base is considered as a knowledge base that relates the traffic state and the signal state. The base includes a set of rules to deduce one or several proposals of messages for each panel according to the measures recorded by traffic detectors. In general, this solution provides the required flexibility to write specific cases corresponding to each type of message (congestion, incident, travel time, etc.). The knowledge base includes also abstraction knowledge. The purpose of this knowledge is to deduce traffic characteristics of higher level of abstraction through data interpretation of information recorded by sensors. The general format of the rules are:

- abstraction rules:

```
IF conditions about the current traffic state
THEN value representing an abstraction of a traffic state
```

- message selection rules:

```
IF conditions about the current traffic state
THEN proposal of a message for a particular panel

IF conditions about messages proposed for panels
THEN proposal of a message for a particular panel
```

For example, the following rule determinates if there are problems of traffic congestion at one off-ramp:

```
IF      (road section A) occupancy > 20,
        (road section B) speed > 80
THEN
        (panel P33) message = traffic jam at N-V.
```

For instance, the following rule determinates that there is an accident in a path if one section's speed is very lower and in the following has a normal speed:

```
IF      (road section A) speed < 30,
        (road section B) speed > 80
THEN
       (path P) potential state = incident.
```

Compatibility Knowledge Base

This knowledge base includes conditions that establish unacceptable combinations of messages in order to avoid inconsistency between messages. This knowledge is formulated using rules that on the right hand side include conditions about incompatibility and, on the left hand side, indicate which panel should change its message. Thus, the format of the rule is:

```
IF      conditions about the current traffic state and
        conditions about messages of several panels
THEN    incompatible panel
```

For instance, a rule can be used to avoid presenting the same message in two consecutive panels P1401 and P2401. In this case, the second panel should change the proposal:

```
IF      (panel P1401) proposed message = M1,
        (M1) type = incident,
        (panel P2401) proposed message = M2,
        (M2) type = incident
THEN
        (panel P2401) incompatible = yes.
```

The rule-based representation is flexible enough to include both general and particular conditions about compatibility according to the requirements of each control center.

Remedy Knowledge Base

This knowledge base includes the criteria with which the detected inconsistencies are solved by modifying a proposed configuration. For the particular case of traffic control, this means to select which panel of a set of panels is required to change the message in order to avoid the inconsistency, and to select a different new candidate message for this panel. This information is deduced partially with the help of the rules of the previous knowledge bases, which on the right hand side select the panel that must change the message. Together with this, it is necessary to have criteria to select another message. For this purpose there is an explicit priority scheme for types of messages defined as follows:

```
Priority level 1:      Type of message T1
Priority level 2:      Type of message T2
Priority level 3:      Type of message T3
....
Priority level N:      Type of message Tn
```

For the case of Madrid the most prioritary level was assigned for the messages of the type incident. The second level was assigned to the traffic jam warning type. The third level was assigned to messages for destination travel time, and so on. The priority of lowest level was assigned for messages about general information (e.g., related to education of drivers) that do not have immediate influence on the behaviour of the traffic.

Thus, when a candidate message is rejected for a particular panel, the general procedure backtracks to select another one within a list of potential messages that are coherent with the current traffic state. The priority scheme is used to select the next message for the panel.

3.2 THE STRATEGY OF INFERENCE

The general inference procedure makes use of the previous knowledge bases following the propose-and-revise strategy with the following steps:

1. *Propose a set of messages*. From the current traffic state, and using the *derivation knowledge*, a set of candidate messages is generated for each panel. This process is performed in three phases. In the first one, from the current traffic measurements, new values about the traffic state are abstracted. Then with this information, a set of candidate messages for each panel is proposed. Finally from the set of candidate messages for each panel, one message is selected by using the priority scheme.

2. *Revise consistency.* From the set of candidate message, and using the *compatibility knowledge*, the proposal is verified to check whether it satisfies the coherence criteria. In case that the criteria are satisfied, the proposal is displayed to the operator of control centre. In other case step number three is performed.

3. *Remedy incompatibility.* From the detected incompatibilities, and using the *remedy knowledge*, a new set of candidate message is proposed. This procedure develops a search in such a way that for each panel that must change the proposal, a new message is selected within the list of candidate messages that are consistent with the traffic state, following the priority scheme defined in the remedy knowledge base.

4. EXPERIENCE AND EXAMPLES

Following this architecture, a system was developed for the city of Madrid, to control the M-40 Urban Ring. This road is a motorway of around 60 Km in both ways that includes a total of 63 panels to present messages to drivers. The road includes the typical information infrastructure for real-time traffic management and operators must decide on real-time the set of messages to be presented in those panels according to the behaviour of the road (traffic jams, incidents, etc.).

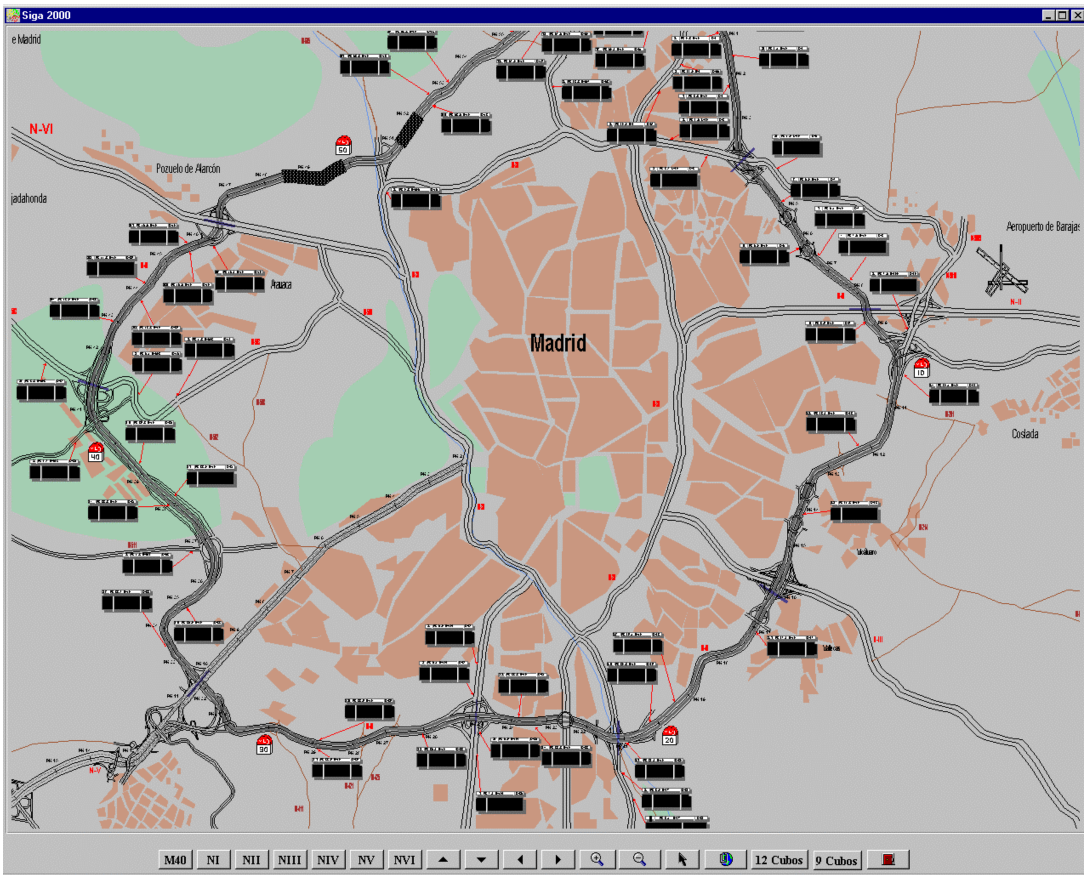

Figure 2: The M-40 motorway of Madrid with variable message panels

Table I and II present an example of the behaviour of the system. Table I show an example of input data for the system, the traffic measurements recorded by sensors. Table II shows the output of the system, the proposed messages for panels.

Detector	Measure	Data	Detector	Measure	Data
Detector D26	Speed	103	Detector D37	Speed	97
Detector D26	Occupancy	8	Detector D37	Occupancy	8
Detector D28	Speed	101	Detector D39	Speed	83
Detector D28	Occupancy	10	Detector D39	Occupancy	22
Detector D30	Speed	75	Detector D41	Speed	45
Detector D30	Occupancy	6	Detector D41	Occupancy	25
Detector D32	Speed	98	Detector D42	Speed	30
Detector D32	Occupancy	3	Detector D42	Occupancy	37
Detector A32	Occupancy	25	Detector D44	Speed	25
Detector D34	Speed	62	Detector D44	Occupancy	40
Detector D34	Occupancy	18	Detector D46	Speed	113
Detector D35	Speed	48	Detector D46	Occupancy	6
Detector D35	Occupancy	35	Detector D48	Speed	105
...	...	...	...	...	...

Table I:. Input data of the system

In a first view, from the traffic measurements some problems of the road can be deduced. For example between road detectors D41 and D44 a decrease of the speed is observed, and due to that the travel time to the road M-607 is a high travel time compared with a normal state of the traffic. Furthermore, the high measure of the road detector A32´s occupancy let us know that there is a traffic jam at N-V Exit since the measure of the occupancy is very high.

Panel	Message	Panel	Message	Panel	Message
Panel P4401	Traffic Jam at N-V Exit	Panel P1511	To M-503 2 Min To N-VI 9 Min To M-607 20 Min	Panel P1503	To N-VI 5 Min To M-607 16 Min
Panel P3401	To N-V 4 Min To M-503 12 Min To N-VI 19 Min	Panel P27	To M-503 2 Min To N-VI 9 Min To M-607 20 Min	Panel P31	To N-VI 2 Min To M-607 13 Min
Panel P2401	To N-V 3 Min To M-503 11 Min To N-VI 18 Min	Panel P29	To M-503 1 Min To N-VI 8 Min To M-607 19 Min	Panel P33	To N-VI 1 Min To M-607 12 Min
Panel P1401	Traffic Jam at N-V Exit	Panel P1513	To N-VI 5 Min To M-607 16 Min	Panel P1605	To M-607 7 Min
Panel P23	Traffic Jam at N-V Exit	Panel P3503	To N-VI 5 Min To M-607 16 Min	Panel P36	To M-607 5 Min
Panel P26	To M-503 4 Min To N-VI 11 Min To M-607 22 Min	Panel P2503	To N-VI 5 Min To M-607 16 Min	Panel P41	To M-607 1 Min
...	...	...	...	...	...

Table II:. Outputs of the system

This system was implemented by using a knowledge modelling software tool, called KSM (Knowledge Structure Manager) developed by our own group [Cuena, Molina, 00] and it was integrated with the rest of the information system to run on-line at the Traffic Control Center of the city of Madrid. The specific software was designed following an object oriented design, and was implemented in C++ . There were about 3000 lines of code C++ specific for the system and about 70000 lines of reused code C++, corresponding to the KSM tool for knowledge representation.

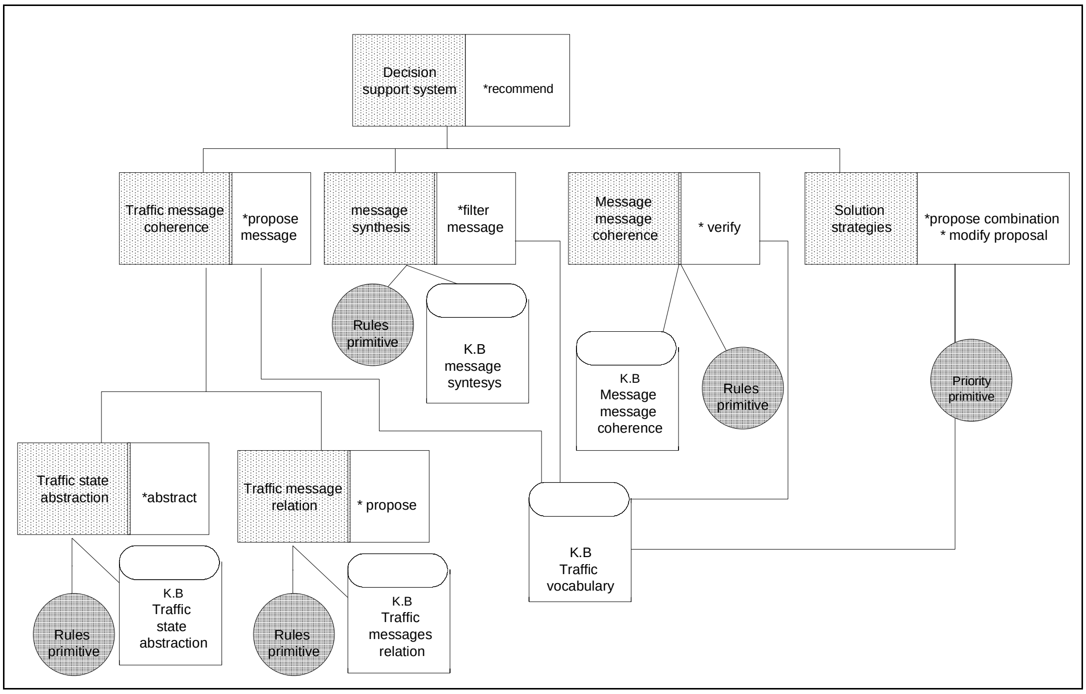

Figure 3: Knowledge organisation using KSM methodology

5. CONCLUSIONS

In summary, the system presented in this paper can be considered an innovative development within the field of transport that takes advantage of the recent advanced proposals for knowledge sharing and reuse in the domain of knowledge engineering in Artificial Intelligence.

In the problem, the qualitative nature of traffic messages together with specific criteria area-dependent, corresponding to heuristic knowledge of the area for specific traffic panels, makes difficult a solution based on generic algorithms. Thus, an approach from the field of Artificial Intelligence, in particular a problem-solving method called propose-and-revise for configuration design problems, has been useful to solve this problem.

The solution makes available on real time strategic knowledge to help operators in selecting the most appropriate state of control devices, taking care every moment the compatibility between the road state and the signal state. This development was carried out for the M-40 urban ring for the city of Madrid and it was installed on-line at the Traffic Control Center of the city.

The resulting software architecture, thanks to the knowledge-based approach, provides an appropriate level of quality from the point of view of easy comprehension and easy maintenance, together with an open and reusable solution for the development of a new control model for different traffic areas.

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